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on behalf of CUORE Collaboration
Universita` di Milano Bicocca
Sez. INFN di Milano
Outline

- Double Beta Decay
- Thermal Detectors
- The first TeO2 experiment: MiDBD
- The running TeO2 experiment: CUORICINO
- The future TeO2 experiment: CUORE
Neutrino oscillation experiments have given convincing evidences that neutrinos are massive and mixed.

**Missing informations:**
- Neutrino absolute mass scale
- Mass hierarchy
- Nature (Dirac/Majorana)
- CP (Majorana) phases

**Double Beta Decay (DBD):**
- \( T_{1/2} = 10^{18} \div 10^{25} \text{ y} \)
- \( m_\nu > 0 \)
- Majorana
- L violation
- \( T_{1/2} \geq 10^{25} \text{ y} \)

**DBD2ν:** \((A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e\)
**DBD0ν:** \((A,Z) \rightarrow (A,Z+2) + 2e^-\)
**DBDχ:** \((A,Z) \rightarrow (A,Z+2) + 2e^- + n_\chi\)

**Phase space factor**

\[ (T^{0N}_{1/2})^{-1} = \sum_k G_k (Q, Z) M_k^2 |<m_\nu>|^2 \]

**Nuclear matrix elements**

\[ \langle m_\nu \rangle \equiv m_{ee} = \sum_k U_{ek}^2 m_k = \sum_k |U_{ek}|^2 \left( e^{i\alpha_ek} \right) m_k \]
TeO$_2$ crystals work as source ($^{130}$Te) and detector (bolometers). The weak thermal coupling ($\sim 4 \text{ pW/mK}$) through the heat sink ($\sim 10 \text{ mK}$) is critical for effective detection. The crystal absorber ($\text{TeO}_2$) has a temperature change given by $\Delta T = \frac{E}{C} \div T^{-3}$. The thermometer (Ge thermistor) detects this temperature change, $\Delta T \Rightarrow \Delta R$. Incident particles or internal DBD0 decays provide the energy input for these processes.
Phases of the exp. on TeO$_2$ at LNGS

Past, present and future:

1997  The first large mass array of bolometers was operated
      20 crystals $\times$ 340 g = 6.8 kg  (Mi DBD - I )

1998-2001  Tests on larger crystals ($\sim$750 g) were successfully carried out
           aiming at more powerful experiments

2001  The 20 crystal array was rebuilt with improved BKG features
       (Mi DBD - II )

2002  A new, larger mass array is assembled
       44 crystals $\times$ 790 g $\approx$ 41 kg (CUORICINO)
           18 crystals $\times$ 330 g

2003-...  Full data taking of CUORICINO  (1$^{\text{st}}$ run: March 2003 - November 2003
           2$^{\text{nd}}$ run: May 2004 - ...)

2004-2009  Construction of a second generation array
           988 crystals $\times$ 760 g $\approx$ 741 kg  (CUORE experiment)
MiDBD-I, MiDBD-II and CUORICINO are installed in a dilution refrigerator (T~10 mK) and surrounded by:
- Cu shields,
- Roman Lead Inner shield,
- nitrogen overpressure,
- 20 cm commercial Lead external shield,
- a Faraday Cage.

MiDBD-II and CUORICINO have an additional 10 cm Borated PET external shield.
MiDBD-I and MiDBD-II

MiDBD-I

- Single detector module
- Large amount of PTFE
- Crystal surfaces treated in China with not radiopure powders

MiDBD-II

- 4 detectors module
- Less PTFE amount
- Crystals surface treatment
  - Cu surface treatment in Legnaro
- Inner Roman lead shield addition
- External 10 cm Borated PET Shield

20 $3 \times 3 \times 6$ cm$^3$ (340 g) TeO$_2$ crystals
  - (16 natural + 4 enriched)

Total mass ~ 6.8 kg
MiDBD-I and MiDBD-II: $<m_\nu>$ results

Statistics:

MiDBD-I: 31.508 kgxh  
MiDBD-II: 5.690 kgxh

FWHM(@2615keV)

MiDBD-I: 9.3 keV  
MiDBD-II: 15 keV

Background (@DBD0ν):

MiDBD-I: 0.59 ± 0.06 c/keV/kg/y  
MiDBD-II: 0.33 ± 0.11 c/keV/kg/y

DBD0ν results:

$T_{1/2}^{130Te} > 2.1 \times 10^{23}$ y  
$<m_\nu> < [1.1 \div 2.6]$ eV

Total statistics: 4.3 kg y
Total mass
~41 kg

**CUORICINO set-up**

- **11 modules** 4 detector each, 5x5x5 cm$^3$ 790 g TeO$_2$ crystals
- **2 modules** 9 detector each, 3x3x6 cm$^3$ 330 g TeO$_2$ crystals

Particular care devoted to selection and cleaning of materials:
- Crystals grown from pre-tested low activity powders
- Crystals surface treatment with low activity materials
- Low activity selected copper faced to the detector
- Copper and PTFE surface cleaning
- Mounting operations in clean environment

10 cm
1 cm
7.5 cm
Collected statistics 1st run

- March 2003-November 2003

Some detector connections were broken; cryogenic problems limiting live time

32 working detectors => 29 used

17 working detectors => 15 used (11 natural + 4 enriched)

3.75 kg * γ of TeO₂

Pulse height distribution

Energy resolution distribution

120 ± 75 μV/MeV*kg

104 ± 35 μV/MeV*kg

7.8 ± 2.5 keV

9.1 ± 3.1 keV
Collected statistics 2\textsuperscript{nd} run

- May 2004 – December 2004

Disconnected detectors recovered; He liquifier disconnected

42 working detectors => 40 used

18 working detectors => 17 used (13 natural + 4 enriched)

\[
\begin{align*}
7.1 \text{ kg} \times \text{y of TeO}_2
\end{align*}
\]

Pulse height

\[
\begin{align*}
167 \pm 99 \mu\text{V/MeV*kg} \\
147 \pm 60 \mu\text{V/MeV*kg}
\end{align*}
\]

FWHM at 2615 keV

\[
\begin{align*}
7.5 \pm 2.9 \text{ keV} \\
9.6 \pm 3.5 \text{ keV}
\end{align*}
\]
Calibration spectra

$^{232}$Th wire source

![Graphs showing calibration spectra for $^{232}$Th wire source with different detector arrangements.](image-url)
Background spectra

**gamma region**

- 5x5x5 cm$^3$ crystals
- 3x3x6 cm$^3$ nat. crystals

**DBD$^0\nu$ region**

- 5x5x5 cm$^3$ crystals
- 3x3x6 cm$^3$ nat. crystals
CUORICINO results

Total Statistics: **10.85 kgxy**

Background (@DBD0ν):

\[ 0.18 \pm 0.01 \text{ c/keV/kg/y} \Rightarrow \text{reduction of } \sim 2 \text{ (4) with respect to MiDBD-II (I)} \]

DBD0ν result:

\[ T_{1/2}^{130\text{Te}} > 1.8 \times 10^{24} \text{ y} \]

\[ \langle m_\nu \rangle < [0.2\div1.1] \text{ eV} \]

arXiv:hep-ex/0501034 v1
CUORICINO sensitivity

**Sensitivity:** Lifetime corresponding to the minimum detectable number of events above background at a given C.L.

\[
F^{0\nu} = 4.17 \times 10^{26} \times \frac{a}{A} \frac{M \Gamma}{b \Gamma} \times \epsilon
\]

For: \( b = 0.2 \) and \( \Gamma = 8 \text{ keV} \)

\[
F^{0\nu} = 4.2 \times 10^{24} \ T^{1/2} \ (68\% \ CL)
\]

\[
< m_\nu > < 0.07 - 0.5 \text{ eV}
\]
Closely packed array of 988 detectors (750 g each)
19 towers - 13 modules/tower - 4 detector/module
placed inside a specially produced refrigerator.
- Cu shields,
- Roman Lead Inner shields,
- 20 cm commercial Lead shield,
- Borated PET,
- nitrogen overpressure,
- a Faraday Cage.

M ~ 741 kg
CUORICINO proves:

- the feasibility of a large bolometric array with the tower-like structure
- that detector performances (signal rise and decay time, pulse height, energy resolution) are not affected by the increase in crystal size (from 330 g to 790 g)

Cuoricino can't be a direct test of Cuore feasibility for what concerns bkg but:

- The **tightly closed structure** of CUORE should give a strong reduction of the bkg operating with the detector in **anticoincidence**
- The **lead shield** designed for CUORE will be optimized in order to practically **cancel** the outside bkg
- **R&D activities** as respect to surface cleaning and material selection will give an additional **reduction** in the bkg contribution in the DBD region
Sources identified as possible responsible for the bkg in the DBD0ν:

- \( \beta \) and \( \alpha \) from TeO\(_2\) surface
- \( \beta \) and \( \alpha \) from surface of materials facing the crystals (the biggest surface is Cu)
- \(^{208}\text{TI}\) multi-compton events (\(^{232}\text{Th}\) contaminations of distant parts)

Estimated contributions to the DBD0n region:

<table>
<thead>
<tr>
<th>Surface</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>TeO(_2) surface</td>
<td>~ 10 (\pm) 10 %</td>
</tr>
<tr>
<td>Cu surface</td>
<td>~ 50 (\pm) 20 %</td>
</tr>
<tr>
<td>Th cont. of the set-up</td>
<td>~ 30 (\pm) 10 %</td>
</tr>
</tbody>
</table>

Evaluated surface contamination level: ~ \(10^{-9}\) g/g in U and Th (of both TeO\(_2\) and Cu)
An evaluation of the background reachable in CUORE with the contamination levels measured so far (MiDBD, CUORICINO and Ge measurements) for the materials commercially at our disposal was made by means of MonteCarlo simulations:

**Bulk contaminations**

- $\text{TeO}_2 \sim 10^{-13}\text{g/g}$
  - $\Rightarrow <2\times10^{-3}\text{ counts/kev/kg/y}$
- $\text{Cu} \sim 10^{-12}\text{ g/g}$

**Surface contamination**

- $\sim 10^{-9}\text{ g/g for TeO}_2$ and Cu
  - $\Rightarrow <7\times10^{-2}\text{ counts/kev/kg/y}$

We aim at reaching AT LEAST a reduction by a factor 10 in Cu surface contamination and by a factor 4 in $\text{TeO}_2$ surface contamination.

Crystals and Copper cleaning procedure under development.
R&D: Cleaning test (September-November 2004)

Cu: etching, electropolishing and passivation
TeO2: etching and lapping with clean powders

Assembling with clean materials
R&D: Cleaning test results

ANTICOINCIDENCE SPECTRUM

- Hall C
- CUORICINO

Counts (a.u.)

Energy [keV]

3000 4000 5000

Reduction of a factor \(\sim 4\) on crystal surface contaminations: milestone of CUORE for this task reached.

Crystal Bulk contamination \(\sim 10^{-14} \text{ g/g}\) in U and Th
CUORE sensitivity

CUORE bkg goal: $0.001 \div 0.01 \text{ c/keV/kg/y}$

- Montecarlo simulations indicate that the present bulk contaminations of the experimental materials commercially available are compatible with a bkg in the DBDO$n$ region $\sim 0.001 \text{ counts / (keV kg y)}$
- The reduction obtained for the crystal surface contaminations reaches CUORE milestone
- A dedicated R&D with respect to material surface cleaning and measurements is under progress in order to reduce their contribution

\textbf{Sensitivity (1$\sigma$):}

\begin{align*}
\text{b=0.01 c/keV/kg/y} \\
\Gamma=5 \text{ keV} \\
F^0_{\nu}=9.2 \times 10^{25} \sqrt{t \text{ y}} \\
\langle m_\nu \rangle=0.02 \div 0.1 \text{ eV} \\
\text{-------------------------------------------------} \\
\text{b=0.001 c/keV/kg/y} \\
\Gamma=5 \text{ keV} \\
F^0_{\nu}=2.9 \times 10^{26} \sqrt{t \text{ y}} \\
\langle m_\nu \rangle=0.01 \div 0.06 \text{ eV} \\
\end{align*}
Conclusions

- **1997 ÷ 2001**: MiDBD-I and MiDBD-II (m = 6.8 kg)
  bkg level in the DBD0ν region: 0.59 => 0.33 c/keV/kg/y
  limit: $T_{1/2}^{\text{130Te}} > 2.1 \times 10^{23}$ y

- **2002 ÷ now**: CUORICINO (m = 41 kg)
  bkg level in the DBD0ν region: ~ 0.18 c/keV/kg/y
  limit: $T_{1/2}^{\text{130Te}} > 1.8 \times 10^{24}$ y

- **2010 ÷ ...**: CUORE (m = 741 kg)
  bkg level goal in the DBD0ν region: ~ 0.01 ÷ 0.001 c/keV/kg/y
  sensitivity: $T_{1/2}^{\text{130Te}} > 9.2 \times 10^{25} \sqrt{t}$ y (worst case)
  $T_{1/2}^{\text{130Te}} > 2.9 \times 10^{26} \sqrt{t}$ y (best case)
\[ \left( T_{1/2}^{0N} \right)^{-1} = \sum_k G_k(Q, Z) M_k^2 |<m_\nu>|^2 = F^{0\nu} |<m_\nu>|^2 \]

<table>
<thead>
<tr>
<th></th>
<th>$^{130}$Te</th>
<th></th>
<th>$^{76}$Ge</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F'$(10^{-13}$ y$^{-1}$)</td>
<td>$&lt;m&gt;(T_{1/2}=1.8E+024)$</td>
<td>F'$(10^{-13}$ y$^{-1}$)</td>
<td>$&lt;m&gt;(T_{1/2}=1.2E+025)$</td>
</tr>
<tr>
<td><strong>QRPA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Staudt et al., 1992 [28]</td>
<td>34</td>
<td>0.207</td>
<td>10</td>
<td>0.148</td>
</tr>
<tr>
<td>Staudt, Muto, Klapdor, 1990</td>
<td>29</td>
<td>0.224</td>
<td>8.9</td>
<td>0.156</td>
</tr>
<tr>
<td>Pantis et al., 1996 [29]</td>
<td>5.22</td>
<td>0.527</td>
<td>1.12</td>
<td>0.441</td>
</tr>
<tr>
<td>Staudt, Muto, Klapdor, 1990</td>
<td>3</td>
<td>0.695</td>
<td>0.73</td>
<td>0.546</td>
</tr>
<tr>
<td>Pantis et al., 1996 [29]</td>
<td>1.24</td>
<td>1.082</td>
<td>0.14</td>
<td>1.247</td>
</tr>
<tr>
<td>Vogel, 1986 [30]</td>
<td>3.96</td>
<td>0.605</td>
<td>0.19</td>
<td>1.070</td>
</tr>
<tr>
<td>Civitarese, 1987 [31]</td>
<td>5</td>
<td>0.539</td>
<td>1.2</td>
<td>0.426</td>
</tr>
<tr>
<td>Tomoda, 1991 [32]</td>
<td>5.03</td>
<td>0.537</td>
<td>1.2</td>
<td>0.426</td>
</tr>
<tr>
<td>Barbero et al., 1999 [33]</td>
<td>7.77</td>
<td>0.432</td>
<td>0.84</td>
<td>0.509</td>
</tr>
<tr>
<td>Simkovic, 1999 [34]</td>
<td>1.79</td>
<td>0.900</td>
<td>0.62</td>
<td>0.592</td>
</tr>
<tr>
<td>Suhonen et al., 1992 [35]</td>
<td>3.13</td>
<td>0.681</td>
<td>0.72</td>
<td>0.550</td>
</tr>
<tr>
<td>Muto et al., 1989 [36]</td>
<td>5.34</td>
<td>0.521</td>
<td>1.1</td>
<td>0.445</td>
</tr>
<tr>
<td>Stoica et al., 2001 [37]</td>
<td>2.44</td>
<td>0.771</td>
<td>0.65</td>
<td>0.579</td>
</tr>
<tr>
<td>Faessler et al., 1998 [38]</td>
<td>2.66</td>
<td>0.738</td>
<td>0.9</td>
<td>0.492</td>
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With the same model of HM claim: $T_{1/2}^{^{130}Te}=2.4\times10^{24}$ y ($\sim2$ y of CUORICINO live time meas.)
**CUORICINO: vs. MidBD-II bkg spectra**

**Gamma region**

- **MiDBD-II**
- **CUORICINO**

**Alpha region**
γ region: - gamma peaks due to \(^{232}\text{Th},^{238}\text{U},^{40}\text{K},^{60}\text{Co}\) (also the sum peak at 2505 keV), \(^{57}\text{Co},^{54}\text{Mn}\) and tellurium activation lines are visible in the bkg spectrum.

α region: - peaks at \(E = E_\alpha + E_R\) due to \(^{232}\text{Th},^{238}\text{U},^{210}\text{Po}\) (rate decreasing in time) are visible in the bkg spectrum.
- peak at \(E = E_\alpha\) of \(^{210}\text{Pb}\) visible in the spectrum.
- peak at 3250 keV.

Comparison with MiDBD:

<table>
<thead>
<tr>
<th>Ratios MiDBD-II / CUORICINO</th>
</tr>
</thead>
<tbody>
<tr>
<td>U and Th gammas</td>
</tr>
<tr>
<td>~0.5</td>
</tr>
<tr>
<td>~1</td>
</tr>
</tbody>
</table>
Crystal bulk contaminations: gaussian peaks at the Q-value of the decay

Crystal surface contaminations: peaks at the $\alpha$ energy with low energy tails

Surface contaminations at a depth $\sim 5 \mu$m of the materials facing the crystals: flat continuum

Evaluated contamination levels:

- Surface: $\sim 1$ ng/g
- Bulk: $< 1$ (0.1) pg/g for Cu (TeO$_2$)
In the computation of the CUORE bkg we have considered the contribution of:
- neutrons and muons => small contribution (possibility of a $\mu$ veto)
- gamma environmental bkg => small contribution thanks to a $4\pi 20$ cm lead shield
- DBD2$\nu$ in the TeO$_2$ crystals => evaluated from the present upper limits of $T_{1/2}^{2\nu}$
- bulk and surface contaminations of the experimental materials
- cosmogenic activation of Te and Cu

Assumed contamination levels:

<table>
<thead>
<tr>
<th></th>
<th>$^{232}$Th</th>
<th>$^{238}$U</th>
<th>$^{40}$K</th>
<th>$^{210}$Pb</th>
<th>$^{60}$Co</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bulk</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TeO$_2$</td>
<td>0.5 pg/g</td>
<td>0.1 pg/g</td>
<td>1 pg/g</td>
<td>10 $\mu$Bq/kg</td>
<td>0.02 $\mu$Bq/kg</td>
</tr>
<tr>
<td>Cu</td>
<td>4 pg/g</td>
<td>2 pg/g</td>
<td>1 pg/g</td>
<td>0</td>
<td>10 $\mu$Bq/kg</td>
</tr>
<tr>
<td>Roman Lead</td>
<td>2 pg/g</td>
<td>1 pg/g</td>
<td>1 pg/g</td>
<td>4 mBq/kg</td>
<td>0</td>
</tr>
</tbody>
</table>

**COSMO**
- 4 months C.R. exposition
- 2 years underground

**Surface**

<table>
<thead>
<tr>
<th></th>
<th>$^{238}$U Bq/cm$^2$(x10$^{-6}$)</th>
<th>$^{232}$Th Bq/cm$^2$(x10$^{-8}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TeO$_2$-$^{238}$U</td>
<td>2 ± 1</td>
<td>-</td>
</tr>
<tr>
<td>Cu-$^{238}$U</td>
<td>5 ± 2</td>
<td>3.4 ± 1.3</td>
</tr>
</tbody>
</table>

Bolometric: CUORICINO

Direct meas. under study: ICMPS, laser ablation...
Bulk: The contribution from C.R. activation of Te and Cu can be lowered by means of an optimization of the production and storage procedure...

| Surface | $^{238}\text{U}$  
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TeO$_2$</td>
<td>1.6e-2 +/- 8.4e-3</td>
</tr>
<tr>
<td>Cu</td>
<td>5.8e-2 +/- 6.6e-3</td>
</tr>
<tr>
<td>Sum</td>
<td>7.4e-2 +/- 1.1e-2</td>
</tr>
</tbody>
</table>

Surface: we need a reduction of an order of magnitude with respect to CUORICINO surface contamination levels!!

Recent measurements performed in hall C with new cleaning procedures have shown a reduction of ~5 in the crystal surface contaminations.
New cleaning procedures (plasma cleaning...) for Cu surfaces are under study.
Recent measurements performed in hall C with new cleaning procedures have shown a reduction of ~ 5 in the crystal surface contaminations.

New cleaning procedures (plasma cleaning...) for Cu surfaces are under study.
From DBD experiments we can have information about:

- L violation
- neutrino nature
- neutrino absolute scale
- mass hierarchy
- CP phases
Neutrino physics situation

$\nu_{\text{atm}}(SK)$: $1.3 \times 10^{-3} \leq |\Delta m_{23}^2| \leq 3.0 \times 10^{-3} \, \text{eV}^2 \sin^2 2\theta_{23} > 0.9$

$\nu_{\text{sol}}(SNO) + \nu_{\text{react}}(\text{kamland, CHOOZ, Palo Verde})$:

$5.6 \times 10^{-5} \leq |\Delta m_{21}^2| \leq 9.2 \times 10^{-5} \, \text{eV}^2 \ 0.23 \leq \sin^2 2\theta_{12} \leq 0.38 \ \sin^2 \theta_{13} = 0$

$6.1 \times 10^{-5} \leq |\Delta m_{21}^2| \leq 8.5 \times 10^{-5} \, \text{eV}^2 \ 0.25 \leq \sin^2 2\theta_{12} \leq 0.36 \ \sin^2 \theta_{13} = 0.04$

Beta Decay (H3) (Mainz and Troitsk): $m_1 \leq 2.2 \, \text{eV}$

Astrophysical data (WMAP): $\sum m_i \leq 0.7 \, \text{eV}$

DBD0$\nu$ (IGEX, H-M): $<m_\nu> < 0.1 \div 0.9 \, \text{eV} \quad \text{H-M claim: } <m_\nu>=0.39 \, \text{eV}$

$<m_\nu>$ possible ranges:

NH) $<m_\nu> \leq 5.5 \times 10^{-3} \, \text{eV}$

IH) $10^{-2} \leq <m_\nu> \leq 5.5 \times 10^{-2} \, \text{eV}$

QDH) $0.42 \ m_1 \leq <m_\nu> \leq m_1$ with $m_1 >> 4.5 \times 10^{-2} \, \text{eV}$
Why $^{130}\text{Te}$

$^{130}\text{Te}$ features as a DBD candidate:

- high natural isotopic abundance (I.A. = 33.87%)
- high transition energy ($Q = 2528.8 \pm 1.3$ keV)
- encouraging theoretical calculations for DBD0$\nu$ lifetime
- already observed with geo-chemical techniques ($\tau_{1/2 \text{ incl}} = (0.7 - 2.7) \times 10^{21}$ y)

Comparison with other candidates:

<table>
<thead>
<tr>
<th>Isotopic abundance (%)</th>
<th>Transition energy (MeV)</th>
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</thead>
<tbody>
<tr>
<td>$^{130}\text{Te}$</td>
<td>$^{136}\text{Xe}$</td>
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</tbody>
</table>

- large phase space ($G^{0\nu}Q^5$), lower background
- $m_{ee} \approx 0.1$ eV $\Leftrightarrow \tau \approx 10^{26}$ y

$0\nu$-DBD half-life (y) for $m_{ee} = 0.1$ eV (different calculations)